ABSTRACT
High input impedance of load and high voltage rise time cause excessive overvoltage at terminals of a PWM-inverter-controlled long cabled load. In this work, performance analysis of overvoltage suppression filter is carried out. The filters considered in this work are the RLC and shunt RC filters. Using transmission line model, parameters for cable connected between inverter output and the load terminals are derived. MATLAB/Simulink software was used to illustrate the voltage response at the load terminal and the performance of the voltage suppression filters.

1. INTRODUCTION
The rapid advancements in power electronic switching devices have contributed to high performance PWM inverters with high-frequency switching operation. However, while these high switching operations can enhance performance of PWM-inverter-fed motors, the sharp voltage rise can degrade the insulation of the motor [1]. In addition, the connection of a long cable between inverter and motor can results in damped high frequency at the terminals of the motor which can stress the motor insulation [1]. Therefore, to minimize high voltage rise at motor terminal, RLC filters is used at inverter output to increase rise time and a shunt RC filters at motor terminals to reduce load impedance at high frequency [2]. The cable connected between inverter and motor is regarded as a transmission line. As a result, transmission line model analysis is used in determining the cable parameters [3].

2. VOLTAGE REFLECTION ANALYSIS OF A LONG CABLE
The behavior of a PWM pulses traveling between an inverter and a motor is similar to traveling waves on transmission lines [3]. Hence, long cables connected between motor and an inverter can be modeled as a transmission line as shown in figure 1. With the use of transmission line model [4], the characteristics impedance of a long cable can be derived as follows.

\[ Z = R + jωL \]  \hspace{1cm} (1)
\[ Y = \frac{1}{G + jωC} \]  \hspace{1cm} (2)
\[ \gamma = \sqrt{(R + jωL)(G + jωC)} \]  \hspace{1cm} (3)

From equation 3, complex propagation constant of a transmission line is computed by finding the square root of the product of the series impedance \( Z \) and shunt admittance \( Y \) of the line [4]. Considering the reflection mechanism that occurs in transmission lines, inverter-cable-motor system can be depicted as shown in figure 2. The inverter output is modeled as an ideal PWM voltage source with the cable characteristic impedance \( Z_0 \) given as the ratio of the series impedance and the complex propagation constant. Equation 4, is further simplified as shown in equation 5.

\[ Z_0 = \frac{R + jωL}{γ} \]  \hspace{1cm} (4)
\[ Z_0 = \sqrt{\frac{R + jωL}{G + jωC}} \]  \hspace{1cm} (5)

If the cable is considered as a lossless system, then the characteristics impedance of the cable becomes

\[ Z_0 = \left| \frac{L}{C} \right| \]  \hspace{1cm} (6)

As shown in figure 2, the motor is modeled by a high-frequency R-C in parallel with a low-frequency R-L model. The forward-traveling voltage waves from inverter output to motor terminal and the backward-traveling voltage waves from motor terminal to inverter output are denoted as \( V(x,s) \) and \( V(x,s) \) respectively. The voltage reflection that occur at the motor terminals is as a results of an impedance mismatch between the cable impedance and the motor impedance [3]. The reflected voltage travels back to the inverter output. However, at the inverter side, voltage reflection reoccurs causing another forward-traveling voltage towards the motor terminals. Reflection coefficient at the motor side is given as

\[ K_L = \frac{Z_L - Z_0}{Z_L + Z_0} \]  \hspace{1cm} (7)

where \( Z_L \) denotes the motor impedance. On the other hand, the reflection coefficient at inverter side is given as

\[ K_C = \frac{Z_C - Z_0}{Z_C + Z_0} \]  \hspace{1cm} (8)

\( Z_L \) represent the inverter impedance.
The sum of forward-traveling and backward-traveling voltage at any point \( x \) is given in equation (9).
Inverter output voltage and motor terminal voltage can be derived by substituting $x = 0$ and $x = l$, respectively, as follows:

$$V(x, s) = V(0, s) + V(l, s) = U(s)\left(1 + \frac{1}{1 - K_L K_R e^{-2\pi s}}\right)$$

(9)

Inverter output voltage and motor terminal voltage can be derived by substituting $x = 0$ and $x = l$, respectively, as follows:

$$V(0, s) = U(s)\frac{1}{1 - K_L K_R e^{-2\pi s}}$$

(10)

$$V(l, s) = U(s)\frac{(1 + K_L) e^{-\pi s}}{1 - K_L K_R e^{-2\pi s}}$$

(11)

3. SIMULATION ANALYSIS

There are a number of methods that are used to suppress overvoltage in PWM inverter fed motors. One method is to connect RLC filter at inverter terminal to decrease voltage rising rate. The other method is to introduce a shunt RC filter at motor terminals to reduce reflection coefficient [4].

3.1 MOTOR TERMINAL VOLTAGE WITHOUT FILTER

Figure 3 demonstrate the voltage response of a PWM inverter connected motor without a filter. The inverter has an output voltage of 150 V with voltage reflection coefficient of 0.9. The motor has a voltage reflection coefficient of 0.8 with the cable having a delay of 0.05 micro seconds. As shown in figure 3b, the motor terminals experience a peak voltage of 270 V.

Another case can be seen in figure 4. In figure 4, an inverter with an output voltage of 300 V and rise time of 0.2 micro seconds causes an overshoot with an approximate value of 550 V.

3.2.1 MOTOR TERMINAL VOLTAGE WITH RLC FILTER

In figure 5, the installation of RLC filter ($R_L = 147 \Omega$, $L_R = 388 \mu H$, and $C_L = 144 \text{ nF}$) at the inverter terminal of the same system in figure 4, reduces voltage overshoot to 13.4% with voltage magnitude of 340.2 V.

3.2.1 MOTOR TERMINAL VOLTAGE WITH RC FILTER

It can further be seen in figure 6, that installation of a shunt RC filter ($R_L = 73.5 \Omega$ and $C_L = 220 \text{ nF}$) in the system in figure 4, also reduces overvoltage to 313.6 V.

4. CONCLUSION

The voltage response of a PWM inverter connected motor over a long cable had been discussed and demonstrated in this work. It was seen in this work that connection of a motor to a PWM inverter output can cause an excessive voltage overshoot. Performance of the two commonly used voltage suppression filters RLC and RC was demonstrated. It was clearly shown that the installation of either RLC or shunt RC filters minimizes the effects of the PWM inverter by reducing the peak voltage at the motor terminals.

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5. REFERENCE